A field study of indoor thermal comfort in the subtropical highland climate of Bogota, Colombia

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Nomenclature

Cll 72-NV	naturally ventilated office
Cll 93-MV	mechanically ventilated office
Cll 100-MM	mixed-mode office

ABSTRACT

This paper undertakes the first field study of indoor thermal comfort in Colombia. The objective of this study was to compare thermal comfort data gathered in office buildings in Bogota, Colombia with the predictions made by three well established standards: ISO 7730:2005 (PMV model), ANSI/ASHRAE Standard 55:2013 (adaptive model) and EN Standard 15251 (adaptive model). The study comprised the administration of a thermal assessment survey to 115 participants and the simultaneous measurement of indoor and outdoor physical variables in 3 offices having different ventilation regimes (natural ventilation, mechanical ventilation and mixed-mode i.e. both natural ventilation and air-conditioning). The findings show that the PMV model incorporated in the ISO 7730 as well as in the ASHRAE standard (which is the standard currently adopted in Colombia for regulating indoor environmental parameters) is able to describe comfort conditions in the mechanically ventilated (MV) office. In the case of the naturally ventilated office (NV), results indicate that the PMV model is not successful at estimating occupants' thermal sensations, and underestimates occupants' perception of discomfort. The EN 15251 adaptive model underestimates thermal discomfort in the NV and MM offices. The ASHRAE adaptive model shows similar patterns underestimating discomfort in the NV office. The findings provide robust evidence that the lack of perceived or actual control in low-energy naturally ventilated buildings strongly reduce occupants' thermal comfort and thus invalidate adaptive model predictions.

1. Introduction

Human thermal comfort has been a subject of research for more than a century, in parallel to the ever more prevalent role of air-conditioning in the market [1]. That research has produced significant findings and developments and has led to the advent of standardisation. Thermal comfort standards have been established in order to allow the measurement and evaluation of those thermal environments humans are usually exposed to [2].

In the late 1960s, P.O. Fanger, pioneer of the thermal comfort research, created a static heat-balance model with the aim of defining a referenced set of indoor environmental variables which were able to provide acceptable thermal conditions to the majority of the occupants [3, 4]. Fanger's model led to the definition of the well known PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) indices which were firstly incorporated into the ISO international standard in 1984.

However, Fanger's model was only intended for application in artificially controlled spaces; the problem of defining thermal comfort conditions in naturally ventilated environments has led to the conceptualization of the adaptive model of thermal comfort which was firstly introduced by Nicol and Humphreys in the 1970s [5] and, then, incorporated in 2004 into the ASHRAE Standard 55 thanks to the research of Brager and De dear [6].

The evidence underpinning those models has been obtained either in climate chambers (Fanger' conventional model) or in actual buildings (adaptive models). Fanger's model is based on experiments conducted in climate chambers in Denmark and the United states [4]. The adaptive model of the ASHRAE Standard 55 is based on data collected in the 1990s by de Dear and Brager as part of the ASHRAE Project RP-884 [6] involving field measurements in Thailand, Indonesia, Singapore, Pakistan, Greece, UK, USA, Canada and Australia. The adaptive model described by Nicol and Humphreys (EN Standard 15251) is based on data collected in the EU Project Smart Controls and Thermal Comfort (SCATs) [7] which involved a 3-years survey of 26 European buildings in France, Greece, Portugal, Sweden and the UK.

Therefore, despite being termed international standards, these standards are based on data from a limited number of geographical regions of the world focusing on Europe, North America, Asia and Australia.

Field studies are fundamental for assessing existing comfort standards in other regions of the world and for developing new algorithms defining comfort conditions in different climates and cultures. The assessment of the applicability of thermal comfort standards requires field data comprising both objective sensor data (air temperature, globe temperature, relative humidity and air speed) and subjective data (actual thermal sensations recorded at the same time as the objective data, thermal preferences etc.).

This paper intends to compare thermal comfort data gathered in a field study in Bogota, Colombia with the comfort predictions and temperature values recommended and regarded as universal by the international comfort standards ISO 7730:2005 [2], ASHRAE Standard 55-2013 [8] and EN Standard 15251 [9].

1.1 Bogota's climatic characteristics

Bogota's local climate is influenced by two key factors: its latitude and its elevation. Bogota's elevation is 2600 m above sea level. It is well known that there is a clear correlation between elevation and average annual temperatures. For this reason, although tropical latitudes are usually associated with tropical climates which are characterized by a lowest mean monthly air temperature never under 18°C [10], the annual average temperature in Bogota is only 14.2°C, between a mean minimum of 8.4°C and a mean maximum of 19.7°C [11]; the region has a subtropical highland climate which is oceanic rather than tropical. The Köppen-Geiger climate classification for Bogota is Cfb [10].

Studies have shown that cognitive and affective expectations - as identified by de Dear [1] - are not take into account in chamber studies [3]. For that reason, field studies of the same populations have shown consistent differences in relation to the comfort temperatures predicted by the Fanger's heat-balance model [1, 12-14]. It has been even suggested that the tropics might require a different level of comfort consideration from that currently provided in the standards [15]. In consequence, existing literature not only indicates that there is room for expanding the study of thermal comfort in tropical regions, but also highlights the fact that not enough internationally-recognised research has been done in the tropical zone of the Americas [16].

Furthermore, the particular climatic conditions of Bogota (which belongs to a tropical area but experiences a subtropical highland climate) are very different than those usually experienced in tropical latitudes. Bogota's climate is characterized by narrow variations of annual temperatures and precipitations distributed all year around, which are typical features of oceanic climates [10]. Therefore, the study of thermal comfort conditions in Bogota is of particular interest for three main reasons:

- to the authors' knowledge, no previous thermal comfort study has been carried out for this type of climate;
- the similarity with an oceanic climate makes extremely interesting to assess if international standards can be applied;
- the benefits of the knowledge that a study on this matter could bring, are not circumscribed to the particular interest of Bogota, but would suit also other cities under the same climatic conditions (subtropical highland climate); for example Pasto and Tunja (regional capitals in Colombia), Quito and Cuenca (national and regional capital respectively, in Ecuador), and Cajamarca (regional capital in Peru). This could potentially help to inform building codes in these countries.

1.2 Colombia's background

The existing building code in Colombia mainly deals with the suitability of the structural response of a building to seismic forces and incorporates some regulations related to fire protection [17]. Thermal comfort in buildings is only regulated by the Standard NTC 5316 [18] which is a Spanish translation of the ANSI/ASHRAE Standard 55. As outlined before, the ANSI/ASHRAE Standard 55 is based on studies from a limited number of geographical regions of the world focusing on Europe, North America, Asia and Australia and, therefore, could fail in predicting neutral temperatures in Colombia; this could consequently affect the need and the design of AC systems leading to higher energy consumptions and obvious environmental issues. Furthermore, the ANSI/ASHRAE Standard 55 categorizes mixed-mode buildings into the air-conditioned group (i.e. under the PMV model) and limits the applicability of the adaptive model to strictly naturally ventilated buildings without mechanical cooling system installed, therefore it is interesting to verify if the adaptive model is also applicable for these "special" mixed-mode buildings which have the potential to reduce energy consumption for cooling [19].

From the adaptive model proposed by ASHRAE, the acceptable operative temperature range for a naturally conditioned space under a mean monthly outdoor temperature of 14.2°C (which is the annual average temperature in Bogota) would be between 18.7°C and 25.7°C for a 80% acceptability (see Figure 1) [8]. Since the temperature in Bogota varies between a mean minimum of 8.4°C and a mean maximum of 19.7°C, the temperature range 18.7°C-25.7°C is easily maintainable inside buildings. This could partially explain the absence of widespread heating or cooling systems in buildings in Bogota. Consequently, it could be argued that a sensible approach to passive design has the potential to produce a thermally comfortable indoor environment without the need of additional conditioning.

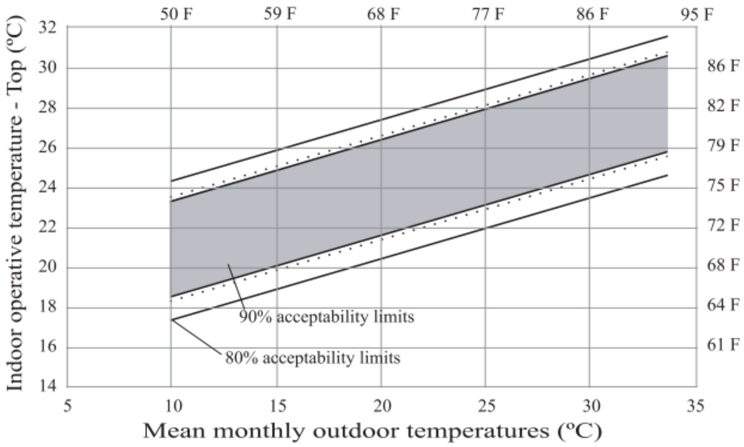

Figure 1 Acceptable operative temperature ranges for naturally conditioned spaces according to the adaptive model proposed by ANSI/ASHRAE Standard 55:2013.

Concerns about climate change are also important drivers in relation to research in thermal comfort. Models presented by the Government of Colombia show that temperatures in Bogota could increase between 2°C and 4°C by the end of the century [20], which would be directly linked to conditions inside buildings and therefore to potential increases in energy consumption.

2. Methodology

2.1 Characteristics of the selected offices

The survey was conducted between the 5th and 12th of August 2011, as a cross sectional data collection in three offices in three different buildings in Bogota. The criteria for selection of the offices were:

- their main ventilation strategies had to be different;
- the occupants' level of activity in all of them had to be similar.

All the selected buildings are situated in the same area of Bogota and all the offices belong to the same company, which provides some degree of similarity in terms of layout, materials, furniture, level of activity and dress code. In all the three offices occupants are allowed to adapt their clothing level. A short description of the three selected offices is reported below:

- Office Building Calle 72 (Cll 72-NV): it is the oldest building of the group, built around 30 years ago. Its façade is a combination of masonry and single glazing. The existing ventilation scheme is based completely on ventilation driven by natural forces (NV) without mechanical cooling system.
- Office Building Calle 93 (Cll 93-MV): this building was constructed 15 years ago. Its façade is single-glazed and although it has some operable windows, the main ventilation scheme in this office is through mechanical ventilation (MV) without mechanical cooling system.
- Office Building Calle 100 (Cll 100-MM): the most recent building, it was finished in 2007. It has mostly a single-glazed façade with masonry frames. Although there was an environmental engineer in the team for ensuring the sustainable design of the building, the office had to finally rely on an air-conditioning system (AC) for ventilation and thermal comfort. However, a part of the building (which includes the surveyed office) is equipped with operable windows and, therefore, can run in free-mode when natural ventilation is sufficient to provide acceptable environmental conditions (i.e. room air temperature lower than 27°C). The surveyed office (mixed-mode office) is free-running during the survey period.

The characteristics of the three buildings support the idea of traditional avoidance of artificial conditioning, but they also highlight the recent tendency to increase the level of thermal control by introducing air-conditioning [21].

Figure 2 Location and photos of the selected buildings (map adapted from Google Maps).

2.2 Distribution of the sample

Each office provided between 35 and 40 data sets for a total of 115 respondents: in Cll 72-NV a total of 40 occupants took part, Cll 93-MV provided 37 questionnaires and Cll 100-MM had 38 participants. Apart from selecting subjects that had the same apparent level of activity (office work), there was no other differentiation or specific targeting in relation to those filling in the questionnaire. Participation was only dependant on the willingness and availability of the workers present at the time of the visits.

Table 1 Distribution of participants by gender.

	No of persons		% of females	
	Overall	**Sample**	**Overall**	**Sample**
Cll 72-NV	54	40 (74%)	67%	63%
Cll 93-MV	61	37 (61%)	62%	65%
Cll 100-MM	60	38 (63%)	65%	71%

Most of the subjects surveyed were between 21 and 50 years old (94%). Nearly 85% of the surveyed population had lived in Bogota more than 15 years, but more remarkable is the fact that 97% of the sample had lived there more than 5 years and none less than one year. These figures safely lead to state that the whole sample can be regarded as naturally acclimatised to the climatic conditions of Bogota [22].
Table 1 compares the demographics of the obtained sample against the overall population in each office. The obtained samples represent more than 60% of the total occupants in each office.

2.3 Questionnaire

The questionnaire was created following the indications given in ASHRAE [8] and ISO 7730 [2] and based on the survey already developed by Cena and de Dear [22]. It included the following information:

- Thermal sensation vote (TSV), measured on the seven-point Likert scale used both in the ASHRAE and ISO standards. Participants could report votes along a continuous scale from -3 to 3 (cold: -3, cool: -2, slightly cool: -1, neutral: 0, slightly warm: 1, warm: 2, hot: 3).
- Comfort vote, intended to record occupants' judgement in relation to the existing thermal load. It proposed one pole (comfortable) and four degrees of discomfort to choose from (slightly uncomfortable, uncomfortable, very uncomfortable and extremely uncomfortable).
- Thermal preference vote (TPV), reported in the scale: much cooler, a bit cooler, no change, a bit warmer, much warmer.
- Thermal acceptability vote (TAV) reported in the scale: generally acceptable, generally unacceptable.
- Perceived level of control over the thermal environment and air quality. Occupants had five different options to choose from: no control, light control, medium control, high control, total control.
- Control strategies used. Occupants had to indicate if the following strategies were present and, if so, how often they were used: operating or adjusting windows, exterior doors, interior doors, thermostats, blinds or drapes, local heaters or local fans.
- Current clothing (see Figure 3).
- Activity levels in the previous 30 minutes (see Figure 3).
- Food/beverage intake in the last 15 minutes (see Figure 3).

What activities have you been engaged in during the preceding hour?

	Sitting quietly	Sitting typing/desk work	Standing still	On your feet working	Walking around
Last 10 minutes?	□	□	□	□	□
The 10 minutes preceding?	□	□	□	□	□
The 10 minutes before that?	□	□	□	□	□
The half hour before that?	□	□	□	□	□

Please indicate whether you have consumed any of the following items within the last 15 minutes

□	□	□	□	□
Caffeinated drink	Cold drink	Hot drink	Cigarette	Snack or meal

Please indicate whether you are wearing any of the items listed below by circulating the appropriate number:
0 = not wearing item / 1 = light weight item / 2 = medium weight item / 3 = heavy weight item

Female					Male			
				Underlayer				
0	1	2	3	Top	0	1	2	3
0	1	2	3	Bottom	0	1	2	3
0	1	2	3	Slip				
				Footwear				
0	1	2	3	Socks	0	1	2	3
0	1	2	3	Shoes	0	1	2	3
0	1	2	3	Pantyhose				
				Midlayer				
0	1	2	3	Short sleeved shirt	0	1	2	3
0	1	2	3	Long sleeved shirt	0	1	2	3
0	1	2	3	Pants	0	1	2	3
0	1	2	3	Shorts	0	1	2	3
0	1	2	3	Dress				
0	1	2	3	Skirt				
				Outerlayers				
0	1	2	3	Sweater	0	1	2	3
0	1	2	3	Vest	0	1	2	3
0	1	2	3	Jacket	0	1	2	3
0	1	2	3	Scarf	0	1	2	3

Figure 3 Questions regarding activity level, food/beverage intake and clothing.

The questionnaire had to be written in Spanish and apart from some guidelines provided by the mentioned ISO standard, all the questions were a free translation from the English version. Additionally, some minor adjustments had to be made, including for example a scarf in the list of possible garments that composed the clothing ensemble.

2.4 Instrumentation

From a selection of commercially available instruments, two were selected for the surveys: the HT30 Heat Stress WBGT Meter supplied by Extech Instruments (www.extech.com), and the Hot Wire USB Logging Anemometer supplied by ATP Instrumentation (www.atp-instrumentation.co.uk). Table 2 compares the range and accuracy for each type of measurement against the requirements of ISO 7726:2001 [23]. It can be observed that the required accuracy for air temperature is not met by either instruments. The lower boundary for air velocity measurements has also not been met, though the accuracy is within the required tolerance. This difference does not detract the general findings from their significance, taking into account that the application of the PMV model relies on a number of assumptions (e.g. about the metabolic rate and clothing insulation values, see 2.6) which influence the overall accuracy level. However, these limitations will have to be borne in mind when evaluating the results.

Table 2 Instrumentation details against those specified in ISO 7726:2001.

	Parameter	Range		Accuracy	
		Instrument	Standard	Instrument	Standard
Extech HT30	Black Globe	0 – 80 °C	10 – 40 °C (1)	± 2 °C	± 2 °C (1)
	Air Temperature	0 – 50 °C	10 – 40 °C	± 1 °C	± 0.5 °C
	Relative Humidity	0 – 100 %	---	± 3 %	---
ATP Hot Wire Anemometer	Air Velocity (v_a)	0.1 – 25 m/s	0.05 – 1 m/s	± 5 %	± (0.05+0.05v_a)
	Air Temperature	0 – 50 °C	10 – 40 °C	± 1 °C	± 0.5 °C

(1) requirements for computing mean radiant temperature

2.5 Measurements and calculations

The survey was conducted in each office as a 'point-in-time' survey which means that thermal sensations and physical parameters at each workstation were recorded at the same time. Measurements were carried out from 9 am till about 4:00 pm. Both instruments were fitted to separate tripods and placed at the workstation in a way that would be representative of the usual position of the subject. Although ISO 7726:2001 [23] recommends placing probes at 0.60 m from floor level (for a seated person when only one measurement is made), this study accepts the recommendation made by ASHRAE 55-2013 [8] in relation to placing the probes above desktop level when strong radiant sources (i.e. PCs) are blocked by furniture. For this reason, all the measurements were made at 0.90 m from floor level.
Further, it is noteworthy that although the ATP Hot Wire Anemometer is not omnidirectional, both ISO 7726:2001 and ASHRAE 113-2009 allow the use of a '*directionally sensitive anemometer* […] *if it is carefully oriented to indicate the true air speed at any test position*' [24]. A smoke test using an incense stick was carried out at every workstation to identify the main direction of the air flow prior to each measurement.
Calculation of the Predicted Mean Vote (PMV) for each set of data was done in Microsoft Excel with a Visual Basic macro routine written according to the computer programme presented in Annex D of ISO 7730:2005. The PPD indices were obtained from the PMV indices [2].
Measurements from the closest weather data station, El Bosque, were used for identifying the outdoor air temperature. Outdoor air temperatures ranged from a minimum of 13.7°C (9th of August at 10:00 am during the survey in Cll 100-MM) to a maximum of 19°C (5th August at 4:00 pm during the survey in Cll 93-MV), which represent the general trend of cooler mornings and warmer afternoons.

2.6 Estimation of clothing insulation and metabolic rate

Using the collected data on clothing ensembles, the overall clo value for each subject was obtained by the summation of the partial insulation values of each garment reported according to tables provided in ISO 9920:2009 [25]. Additionally, the insulating effect of the chair was brought into consideration by applying the 0.15 clo estimation made by Cena and de Dear [22] for similar types of chairs. Even though this approach is the most widely used, it relies on the subjective understanding that occupants have of the weight of their pieces of clothing, or even where a specific garment should be reported. This study found values (without considering insulation from the chair) between 0.26 clo and 1.48 clo. Although the final average values in each office accord to the expectations (0.94 clo, 0.81 clo and 0.80 clo), the extremes could indicate errors in these data. For example, a clo of 0.3 would be equivalent to an ensemble of bra and pants plus t-shirt, shorts, light socks, sandals; and a clo of 1.4 would represent an ensemble of underwear (short sleeves/legs) plus boiler suit, insulated jacket and trousers, socks, shoes [26]. It would seem unlikely – though not impossible – that both ensembles would be recorded within the same working environment and weather conditions. Possible sources of errors could be errors during data entry or due to inaccurate self-reporting by the participants. Therefore, even though most clo values are estimates and errors of up to 20% are expected in the estimation of typical ensembles [26] any significant outliers in our analyses are discounted.

The description of the activity level during the last hour was converted into met units by applying the tables provided in the standards (ASHRAE 55-2013 [8], ISO 7730:2005 [2], ISO 8996:2004 [27]). Following the approach of Rowe [28], weighting factors were applied to those activities according to their time band: 50% for activities during the last 10 minutes, 25% for those in the preceding 10 minutes, 15% for those in the 10-minutes lapse before that and finally 10% for the previous half an hour. Similarly, adjustments were made according to previous food/beverage intake (last 15 minutes): 5% added for beverages or cigarette, while 10% for snacks or meals. Average metabolic rates in the surveyed offices were close (1.33 met, 1.35 met and 1.30 met). Although these values are in the upper region of a sedentary activity, they represented correctly the general level of activity of these offices, which had an operation linked directly with the sales force.

3. Results and discussion

3.1 Thermal sensation votes vs. PMV

In this section, standard predicted values and comfort ranges (ISO 7730:2005, ANSI/ASHRAE Standard 55:2013 and EN Standard 15251) are compared with actual comfort votes gathered in the survey. The first comparison is between the model-obtained PMVs and the questionnaire-recorded Thermal Sensation Votes (TSVs). Figure 4 shows box plots of PMVs and TSVs for the three offices. Looking at the means (i.e. the diamonds within the boxes), the PMV model successfully predicts that the mean thermal perception in Cll 93-MV and Cll 100-MM is between -0.5 and 0.5 (i.e. neutral). Regarding Cll 72-NV, it also places this office within that range, which demonstrates that it fails to predict that the real mean thermal sensation is ‘slightly cool’ (i.e. -1). From the boxplot of the vote distributions (Figure 4) it can be seen that ISO predicted PMVs do not approximate the actual thermal vote distributions in the three offices since the PMV model underestimates the actual discomfort, especially for the naturally ventilated environment. This points to a better capability of the model in predicting average perception than voting distribution.

From the boxplot of the predicted and actual votes distributions for Cll 72-NV it can be noticed that the actual votes range from 1 to -3 while the predicted ones range from 1 to -1. As a consequence, the mean PMV overestimates by 1 scale point the actual mean “slightly cold” thermal sensation recorded in the natural ventilated office.

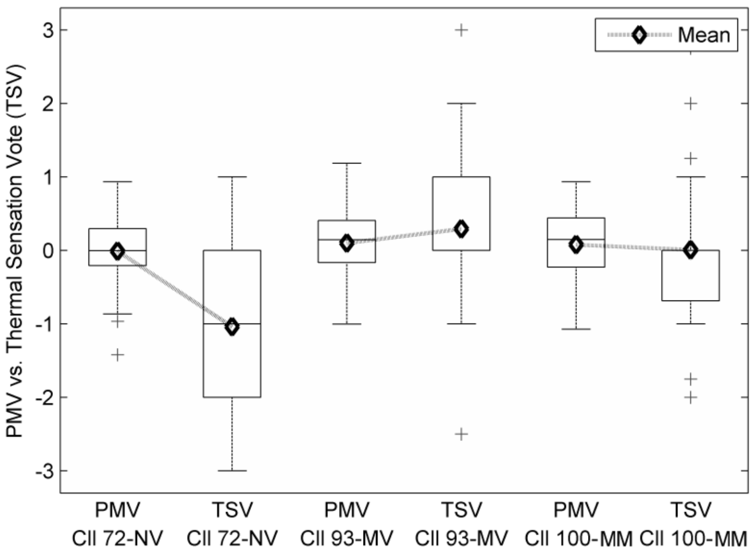

Figure 4 Box plot of PMV and TSV votes for the three office buildings (NV, MV and MM). The line within each box is the median, the diamond is the mean, the edges of the box are the 25th and 75th percentiles (indicated as q1 and q3 respectively), the thin lines (whiskers) extend to those values between q3 - 1.5(q3 – q1) and q1 + 1.5*(q3 – q1), and values outside this range (outliers) are plotted individually as crosses.*

The mean of the PMVs for Cll 93-MV and Cll 100-MM is around 0.1, while for Cll 72-NV is - 0.01, these values correspond to a mean PPD of 8.9%, 10.4% and 10.2% for Cll 72-NV, Cll 93-MV and Cll 100-MM respectively (Table 3). This means that, according to the ISO predictions, about 90% of the occupants are thermally comfortable in the three offices. This value can be compared with the percentage of occupants who gave thermal votes between -1 and 1[1], i.e. 62%, 85% and 80% for Cll 72-NV, Cll 93-MV and Cll 100-MM respectively (Table 3). This comparison confirms that the ISO PMV model underestimates the actual discomfort in the case of the naturally ventilated office.

Table 3 Statistical summary of PMV and PPD indices and Thermal Sensation Votes (TSV)

	Cll 72-NV	**Cll 93-MV**	**Cll 100-MM**
Number of sets[2]	*39*	*34*	*35*
Mean PMV	-0.01	0.1	0.08
Mean PPD	8.9%	10.4%	10.2%
Mean TSV	-1.04	0.3	0.01
$-1 \leq TSV \leq +1$	62%	85%	80%

If the 80% acceptability criterion were used, i.e. declaring a thermal environment as comfortable when 80% of occupants are feeling between ‘slightly cool’ (PMV=-1) and ‘slightly warm’ (PMV=+1) (ISO 7730:2005), the PMV model would predict that all the surveyed offices in Bogota be regarded by their occupants as thermally comfortable. However, applying the same criteria for the observed TSVs there is agreement with the PMV prediction only for Cll 93-MV and Cll 100-MM (85% and 80% of their occupants within the

[1] According to the responses to the second question of the questionnaire, 98% of the comfort votes (people describing their thermal environments as ‘comfortable’) belong to subjects that described their thermal perception between ‘slightly cool’ and ‘slightly warm’, confirming the choice of a comfort range for TSV between -1 and 1.

[2] The sample for the PMV calculation was reduced because of the lack of realistic information about six clothing ensembles. Additionally, one set of data was excluded because its air speed (1.24 m/s) was above the limit accepted for using this index (0 m/s to 1 m/s).

reference band), while Cll 72-NV clearly does not meet the criterion (62%). As already noted above, this difference is due to the PMV underestimation of the votes on the cool side (i.e. "slightly cool", "cool" and "cold") encountered in the naturally ventilated office.

Table 4 Distribution of PMV values

PMV	-3	-2	-1	0	1	2	3
Cll 72-NV	0%	0%	13%	80%	8%	0%	0%
Cll 93-MV	0%	0%	14%	68%	19%	0%	0%
Cll 100-MM	0%	0%	13%	68%	18%	0%	0%
Overall	0%	0%	13%	72%	15%	0%	0%

This underestimation of the model has already been noted in other studies [29] but it contrasts with the literature where it is commonly observed that the PMV model mostly overestimates warm and cold sensations in naturally ventilated buildings [12] [30]. In this regard two main facts need to be pointed out:

- the extreme TSV points in the NV office were measured from 9:30 am to 10:30 am, at a time where the occupants had just entered the building which was in the process of warming up;
- Cll 72-NV had the biggest proportion (65%) of subjects reporting unavailability of personal control (*i.e.* no control, see Table 5). In fact, natural ventilation in Cll 72-NV is mainly given by grates placed above the windows which cannot be easily controlled by the occupants since some of them are permanently open.

Taking into account those facts, the extreme votes could therefore be related to the mutual influence of two aspects:

- the lower initial temperatures of the office in the process of warming up;
- the higher expectations of occupants who had just arrived in the office which could not be met by any control available (the entrance of early-morning cold air in the office could not be avoided by closing the grates).

Despite the fact that the PMV model includes some adaptation factors such as the possibility of adjusting clothing, it does not take into account of other more complex psychological aspects which can drive the judgement of a thermal environment. In this case, some unexpected factors for a natural ventilated office such as high thermal expectation and low personal control (i.e. the occupants' inability to control the ventilation grates) could be considered responsible for the inadequacy of the model. This demonstrates that the PMV model fails in predicting conditions for naturally ventilated buildings when occupants' expectations are very high (higher than those normally experienced in climate chambers). It also provides powerful support for the requirement in the adaptive comfort standards that occupants of naturally ventilated buildings must be able to control the ventilation by manipulating openings [8].

Relative humidity in the surveyed offices was found to be within a reduced range: 30% to 44%. These figures show that relative humidity was at a level regarded as 'normal', and within the limits recommended by ASHRAE [8].

3.2 Thermal sensation votes vs. Adaptive models

Apart from the comfort criteria based on the heat-balance approach, ASHRAE 55-2013 does incorporate a method based on the adaptive approach to thermal comfort. According to this standard, when the main ventilation strategy of a building is naturally-driven i.e. without mechanical cooling installed (this definition excludes the MM buildings in the free-running category) and occupant-controlled, two sets of operative temperature limits based on the prevailing mean outdoor air temperature can be used to establish the ranges of operative comfort temperatures for 80% and 90% acceptability. The monthly mean outdoor temperature during the survey period is equal to 14°C. The corresponding temperature limits which can be derived from the ASHRAE adaptive relation (Figure 1) are equal to 18.6 °C and 25.6 °C for the 80% acceptability limits.

Also the EN Standard 15251 includes a method for calculating the range of acceptable summer indoor temperatures for free-running buildings where occupants are able to access openable windows and are free to change clothing (this definition includes MM buildings in the free-running category). The temperature limits associated with a monthly mean outdoor temperature of 14 °C are equal to 19.42 °C and 27.42 °C for 85% acceptability (PPD < 15%).

ASHRAE and EN Standard 15251 limits are plotted in Figure 5 together with the limits given by the new relation developed by Humphreys correlating neutral temperatures with prevailing mean outdoor temperatures [31].

Box plots of operative temperatures To and comfort operative temperatures ComTo are also shown in Figure 5. Comfort operative temperatures are those temperatures which correspond to thermal votes between -1 and 1 on the perception scale (i.e. central neutral category). As noted earlier, for the MV and MM office 85% and 80 % of the votes are within the central neutral category, while for the NV office only 62 % of the votes are within it.

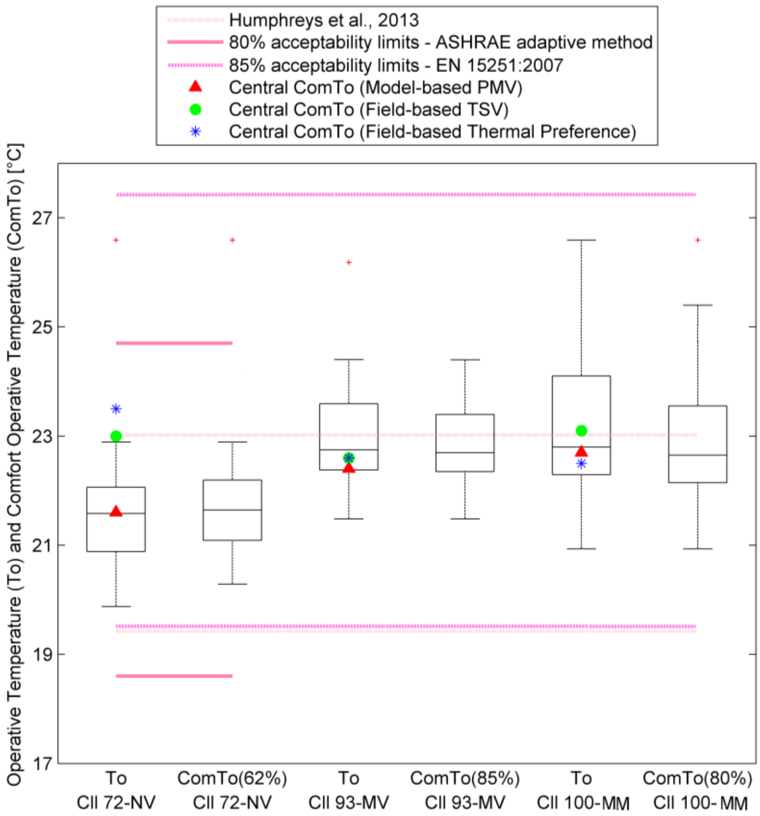

Figure 5 Comparison of comfort temperature ranges for NV, MV and MM. Box plot of To and ComTo for the three office buildings (NV, MV and MM). The line within each box is the median, the edges of the box are the 25th and 75th percentiles (indicated respectively as q1 and q3), the thin lines (whiskers) extend to those values between q3 - 1.5(q3 – q1) and q1 + 1.5*(q3 – q1), and values outside this range (outliers) are plotted individually as red crosses.*

All the operative temperatures for the NV office are within the ASHRAE adaptive range of 80% acceptability and the EN adaptive range of 85% satisfaction (see Figure 5); however, only 62% of the occupants found the NV environment comfortable. Therefore the ASHRAE and EN adaptive methods underestimate the discomfort in the naturally ventilated office. This

is further evidence of the impact of the availability of personal control (i.e. inoperable ventilation grates) in Cll 72-NV compared to what is normally experienced in natural-ventilated environments. This fact lessens the adaptation possibilities of the occupants and causes the inadequacy of the adaptive relations.
The 85% acceptability range from the EN Standard 15251 is good at approximating the level of comfort in Cll 93-MV (85%), but it fails in predicting the level of acceptance in Cll 100-MM (80%) and Cll 72-NV (62%).

From the boxplot of the temperature distributions in Figure 5 it can be further noted that Cll 100-MM has the largest range of operative and comfort temperatures (a 5°C temperature band ranging from 21°C up to about 26°C), while the naturally ventilated building has the narrowest range (only 3°C temperature band from 20°C to 23°C). This is in disagreement with many field studies in which people in naturally ventilated environments are found to accept a wider range of temperatures. This also contrasts with the expectation that the air-conditioned office should provide a tighter control over thermal conditions [12]. The large temperature range in Cll 100-MM is due to a managerial decision over the setting conditions of the AC system, rather than to a poor design of the system (i.e. a design based on an underestimation of the heat load). In the air-conditioned office the temperature for the activation of the cooling unit is set very high (27°C) and occupants can open the windows when the AC is off (mixed-mode operation), therefore temperatures are allowed to vary much more than in a conventional strictly controlled air-conditioned environment. Despite the large temperature variation, the PMV model (which is derived from climate chamber experiments where environmental conditions are almost constant, i.e. steady-state variations) gives reliable predictions. This is due to the fact that, despite running in free-mode, the office has a reduced number of openable windows (see Section 3.3) and, therefore, occupants' perceived control is comparable to that experienced in air-conditioned environments where, notoriously, occupants have low personal control.

3.3 Occupants' use of adaptive controls

Occupants had five different options to choose from when asked about their level of control (no control, light control, medium control, high control, total control). Overall, 47% of them declared to have no control over the thermal conditions of their workplace, and around the same proportion described it as 'Low' or 'Moderate'. In terms of offices, Cll 72-NV had the biggest proportion of subjects reporting unavailability of personal control (65%), followed by Cll 100-MM (50%), while only 24% of occupants shared that level in Cll 93-MV. Overall, a 'High' or 'Total' level of control was not widely accessible (9% overall), which is not a surprise in buildings that have mechanical ventilation or air conditioning as their main ventilation strategy. However, in the mixed-mode free running office and in the naturally ventilated office the level of perceived control is lower than is normally experienced.

Table 5 Distribution of level of control

	No control	Low	Moderate	High	Total
Overall	47%	21%	23%	5%	4%
Cll 72-NV	65%	8%	20%	5%	3%
Cll 93-MV	24%	30%	27%	8%	11%
Cll 100-MM	50%	26%	21%	3%	0%

Different control strategies were suggested in the questionnaire in order to establish whether they were present and, if so, how often were they used. These strategies involved operating or adjusting windows, exterior doors, interior doors, thermostats, blinds or drapes, local heaters or local fans. Table 6 presents a summary of existing strategies in each office. This table was generated taking into account answers only from those who selected a level of control between ‘Low’ and ‘Total’ (i.e. excluding those from occupants who reported ‘No control’). Besides this, answers were divided into ‘Present/Used’ (strategy is present and is used) and ‘Not present/Not used’ (strategy is not present or it is present but is not used). The most common control strategies found were operation of windows and adjustment of blinds or drapes (41% and 46% respectively). On the other hand, the least used were operation of a thermostat and switching on/off a local heater (2% and 3% respectively). From Table 6 it is clear that there is a reduced existence/operation of openable windows for the mixed-mode free running office and the naturally ventilated office.

Table 6 Occupants' use of adaptive controls

		Window	**Exterior door**	**Interior door**	**Thermostat**	**Drape /blind**	**Heating**	**Fan**
Overall	P/U	41%	19%	18%	2%	46%	3%	8%
	Not P/U	59%	81%	82%	98%	54%	97%	92%
Cll 72-NV	P/U	25%	28%	20%	3%	38%	5%	5%
	Not P/U	75%	73%	80%	98%	63%	95%	95%
Cll 93-MV	P/U	59%	16%	19%	0%	49%	0%	11%
	Not P/U	41%	84%	81%	100%	51%	100%	89%
Cll 100-MM	P/U	39%	13%	16%	3%	53%	5%	8%
	Not P/U	61%	87%	84%	97%	47%	95%	92%

P/U= Present/Used, Not P/U=Not Present/Not Used

3.4 Compliance of the neutral temperatures with the standards

It is not enough to describe an existing environment as comfortable or uncomfortable. By means of regression of collected or calculated data it is possible to obtain the temperature at which the subjects in the study are thermally neutral (i.e. they would have selected ‘Neither hot nor cold’ in the questionnaire). In Table 7 and Figure 5 different central comfort temperatures Central ComTo (i.e. neutral temperatures) are reported; they represent the results of different regression analysis:

- Central ComTo (Model-based PMV): it is based on the regression of mean PMV binned in 0.5 To intervals. Central ComTo happens when PMV=0 (see Figure 6, Figure 7 and Figure 8).
- Central ComTo (Field-based TSV): the same method used in (1) but based on TSV (see Figure 6, Figure 7 and Figure 8).
- Central ComTo (Field-based Thermal Preference): regression of mean Preference Votes binned in 0.5 To intervals. Preferred operative temperature ComTo happens when the regression line intersects the 0 (no change) Preference Vote.

Table 7 Central comfort temperatures ComTo in the three offices as calculated by the three different methods illustrated above

	Cll 72-NV	**Cll 93-MV**	**Cll 100-MM**
Central ComTo (Model-based PMV)	21.6°C	22.4°C	22.7°C
Central ComTo (Field-based TSV)	23°C	22.6°C	23.1°C
Central ComTo (Field-based Thermal Preference)	23.5°C	22.6°C	22.5°C

Table 7 suggests that the estimated values of the neutral operative temperatures for Cll 93-MV and Cll 100-MM are quite similar in the three different methods and they approximate the median of the distributions of To fairly well (see Figure 5). This vicinity with the median is explained by the high percentage of comfortable occupants in Cll 93-MV and Cll 100-MM. However, for the NV office the situation is slightly different: the estimation based on PMV is the one giving the best approximation of the median of the box plot, while values based on TSV and Thermal Preference Votes are much higher, around 23°C. This difference reveals the inability of PMV to predict neutral temperatures for the NV office.
Neutral temperatures for the three offices are quite similar around 23°C; therefore the natural ventilated office does not imply lower neutral temperatures; this is a further confirmation of the higher thermal expectations in CII 72-NV compared to conventional natural ventilated environments. The MM office has the largest range of operative and comfort temperatures, while the NV office has the narrowest range. This is due the particular setting conditions of the AC system as seen before (see Section 3.2).

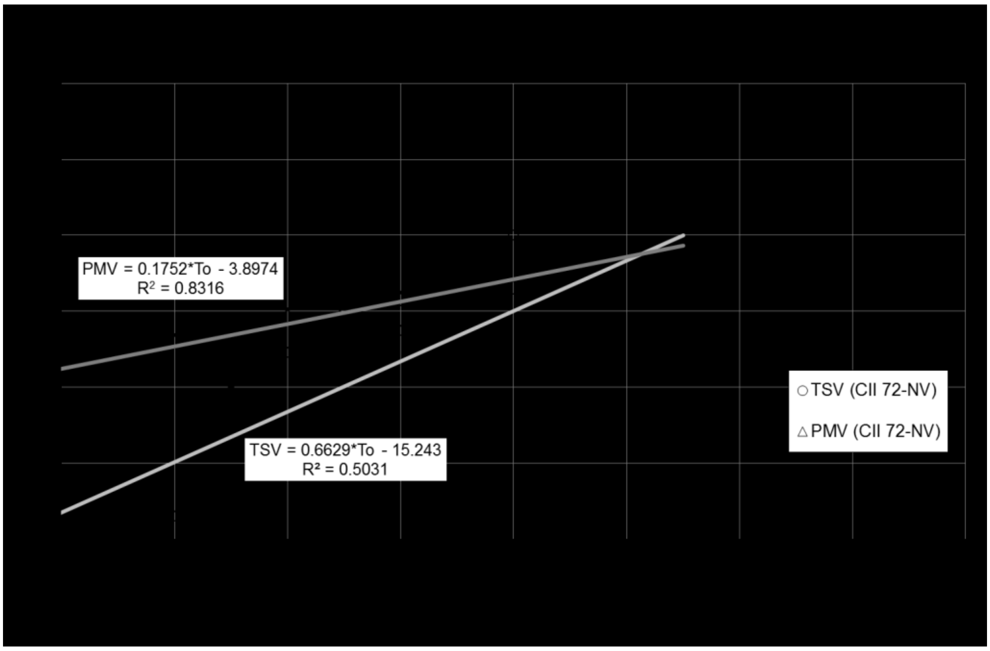

Figure 6 Linear regressions of PMV and TSV vs. Operative Temperature for CII 72-NV

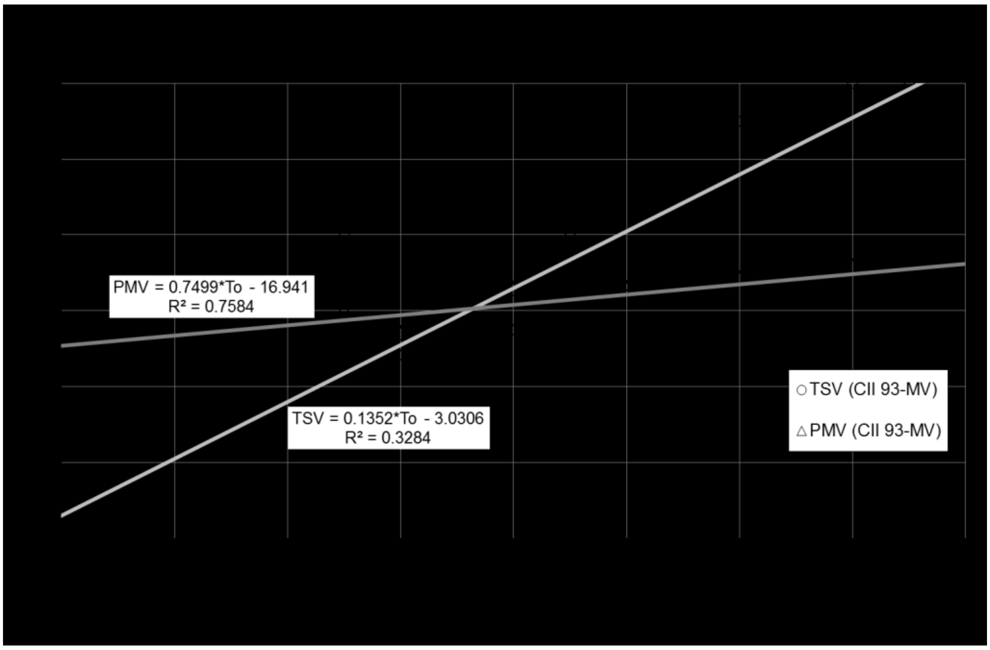

Figure 7 Linear regressions of PMV and TSV vs. Operative Temperature for CII 93-MV

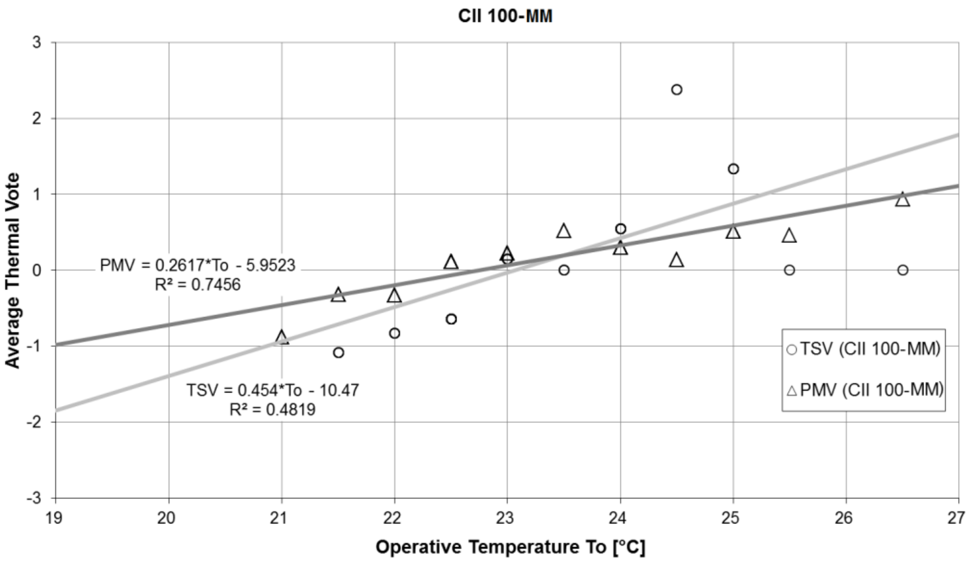

Figure 8 Linear regressions of PMV and TSV vs. Operative Temperature for CII 100-MM

4. General discussion of the findings

The findings can be easier understood looking at the simplified qualitative plot of Figure 9 which shows three possible level of occupants' expectations (Low, Medium, High in the y-axis) and three possible degrees of occupant's control (Low, Medium, High in the x-axis). The PMV/PPD derives from climate chamber studies which are characterized by low control and medium expectations (yellow area). The EN Standard 15251 adaptive model derives from field studies in natural ventilated and mixed buildings characterized by medium/high control and low/medium expectations (green area). The three black symbols represent the three surveyed buildings: Cll 72-NV (star, high expectations and very low control), Cll 100-

MM (circle, medium/high expectations and low control), Cll 93-MV (triangle, medium expectations and low/medium control).

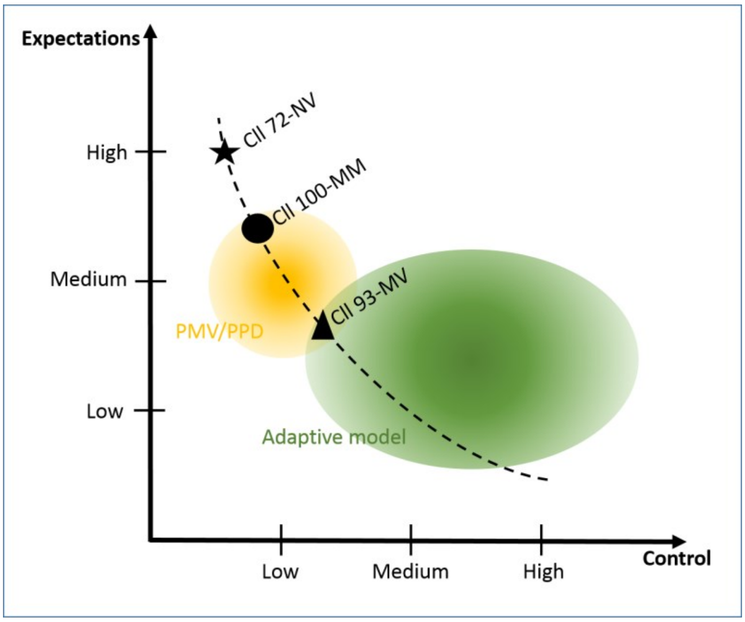

Figure 9 Degrees of occupants' expectations and control in the three surveyed offices

ISO-7730 PMV model is able to estimate the mean thermal perception in the mechanically-ventilated and in the mixed-mode free-running office (circle and triangle inside the yellow area), but it fails to predict that the mean thermal sensation in the naturally ventilated office is 'Slightly cool' (star outside the yellow area). The above result is due to the lack of control in the naturally ventilated office (i.e. inoperable ventilation grates) which exacerbate occupant's expectations. Also, the PMV model is successful at estimating the neutral operative temperature for the mechanical-ventilated and the mixed-mode free-running office, but not for the naturally ventilated one.
The EN Standard 15251 adaptive relation is able to model thermal comfort conditions in the mechanical-ventilated office (triangle inside the green area) but is found to underestimate the discomfort in the mixed-mode free-running office and in the naturally ventilated one (circle and star outside the green area). This can be explained by the reduced availability of personal control in the two offices, which lessens the adaptation possibilities of the occupants.

5. Conclusions

ISO-7730 predicted values and ASHRAE-55 and EN Standard 15251 comfort temperature bands have been compared with actual physical data and comfort votes gathered in a field study in Bogota, Colombia consisting of three offices having different ventilation regimes (natural forces NV, mechanical ventilation MV and mixed-mode MM i.e. both natural ventilation and air-conditioning). Our findings show that the PMV and adaptive model incorporated in the ASHRAE standard (which is the standard currently adopted in Colombia for regulating indoor environmental parameters) is able to predict mean thermal perception in mechanically-ventilated environments in Bogota. This conclusion could also be extended to other cities under the same subtropical highland climate. However, we cannot draw similar conclusions regarding the applicability of the EN and ASHRAE adaptive models to naturally ventilated and mixed-mode free-running buildings since the reduced availability of personal control over the windows in the two surveyed offices invalidates model predictions. More field studies in NV and MM offices are needed to verify the applicability of the EN and ASHRAE adaptive relations.

From the findings it also emerges that the applicability of PMV/PPD and adaptive models is closely dependent to the possibility of controlling the windows given to the occupants. Therefore a classification of spaces based on the level of windows control is more realistic than only considering the presence of an AC unit. For example, we showed that the PMV model is able to predict comfort conditions in the MM free-running office where the low level of occupants' perceived control is comparable to that experienced in air-conditioned environments.

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